White Paper
Sustainability
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Advanced Automation Fuels the Growth of Carbon Capture as an Environmental Solution

Fossil fuels remain a major factor in the energy economy, but carbon capture can reduce their environmental impact.

Here's a quick question: what's the difference between gray hydrogen and blue hydrogen? Both are made from natural gas, so how does one get a better environmental designation? It's all about carbon dioxide.

When gray hydrogen is manufactured, all the carbon dioxide created from the natural gas feedstock is released to the atmosphere. Compounding the problem, all the carbon dioxide from the natural gas used as fuel during reforming is also released. Huge volumes of gray hydrogen are manufactured for use as a chemical feedstock for oil refining and ammonia production, and it remains the most widely applied method for hydrogen supply.

On the other hand, blue hydrogen uses the same natural gas reforming process, but supplements it with carbon capture and storage (CCS). This process captures most of the carbon dioxide produced before it's released into the atmosphere for permanent underground storage. In many applications, this carbon dioxide is injected into active oil wells for enhanced recovery, but in a growing number of situations, it is simply stored underground permanently in natural formations, such as a deep saline aquifer. In this context, CCS reduces the greenhouse gases released for hydrogen production, mitigating overall carbon footprint, and earning the blue designation.

CCS can be used in any number of combustion processes, however it is most effective and economical where the carbon dioxide stream concentration is especially high, such as with chemical processing and refining, and with cement and steel manufacturing.

Combatting climate change

While efforts to develop renewable energy resources are advancing, the world is still largely dependent on fossil fuels and will remain so for many years. CCS reduces greenhouse gas emissions from many stationary sources, and it can be implemented across a wide range of scales at reasonable cost. As a result, CCS is one of the most practical, robust, and efficient emissions reduction solutions available today.

CCS deployments are also growing rapidly (Figure 1). According to the International Energy Agency (IEA), the amount of carbon dioxide captured annually is projected to grow from 40 million metric tons in 2020 to around 6.9 billion metric tons by 2070, with CCS contributing nearly 15% of all emissions removed. As of 2020 there were about 26 commercial-scale CCS projects operating worldwide, now the count has grown to 135 sites, with projections of about 200 new facilities coming online by 2030, capturing over 220 million tons of carbon dioxide per year.

That said, CCS is not free. While the process is straightforward, it is energy-intensive in its own right, and therefore there are calls for careful management to avoid making the solution problematic.

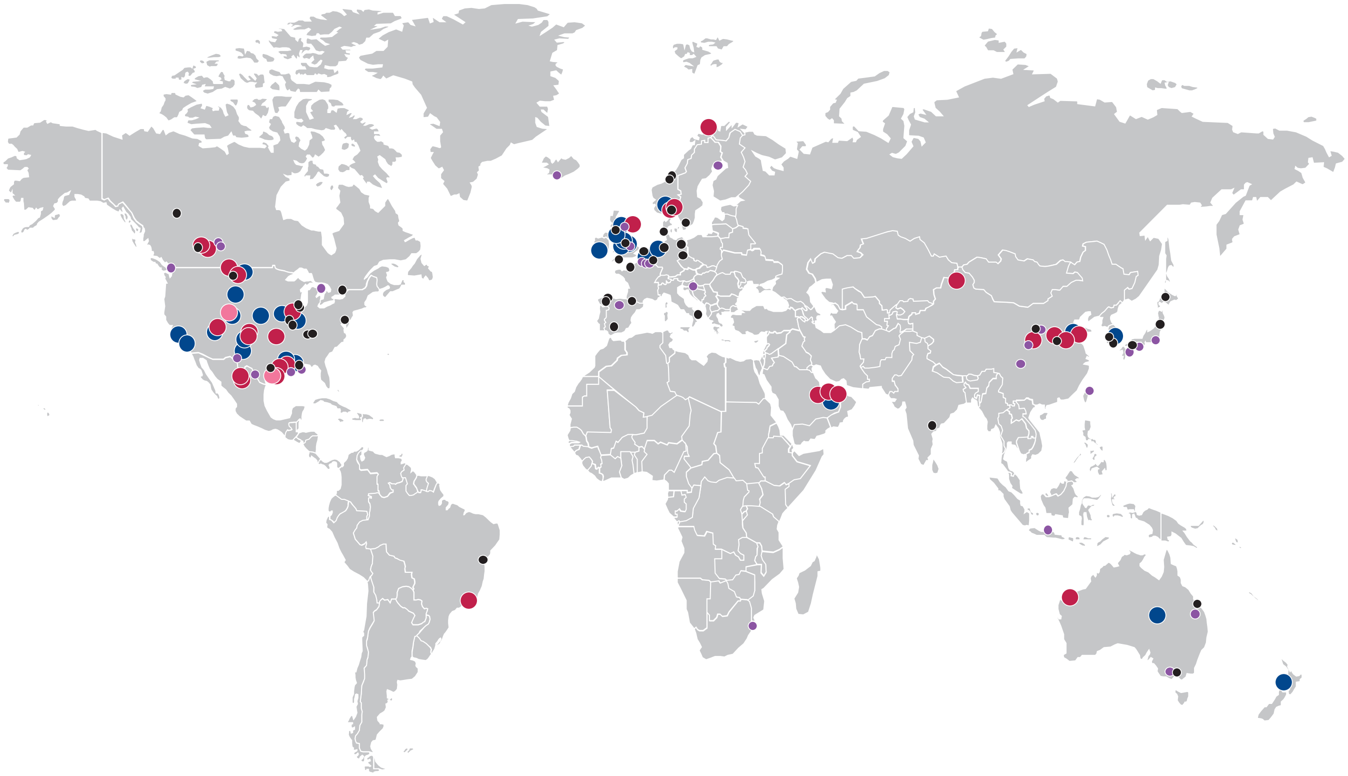

Figure 1: *Implementation of CCS projects are growing worldwide.*

Improving CCS performance

To understand how CCS performance can be improved, let’s take a brief look at how the process operates (Figure 2):

- A CCS unit integrates with one or more sources of carbon dioxide at a given site, typically flue gas streams or chemical process effluent.
- The carbon dioxide-rich gas stream is cooled and filtered, and then injected into an absorber vessel where a liquid solvent captures carbon dioxide, while other gases (hydrogen, nitrogen, etc.) pass through.
- Saturated solvent passes into a stripping reactor where carbon dioxide is forced to bubble out.
- Regenerated solvent flows back into the absorber, so the process runs continuously. Various solvents can be used, and the method to force carbon dioxide out of the liquid takes different forms, but this unit has its own energy requirements.
- Once the stream of carbon dioxide is isolated and purified, carbon dioxide is compressed and sent out via pipeline or tankers.

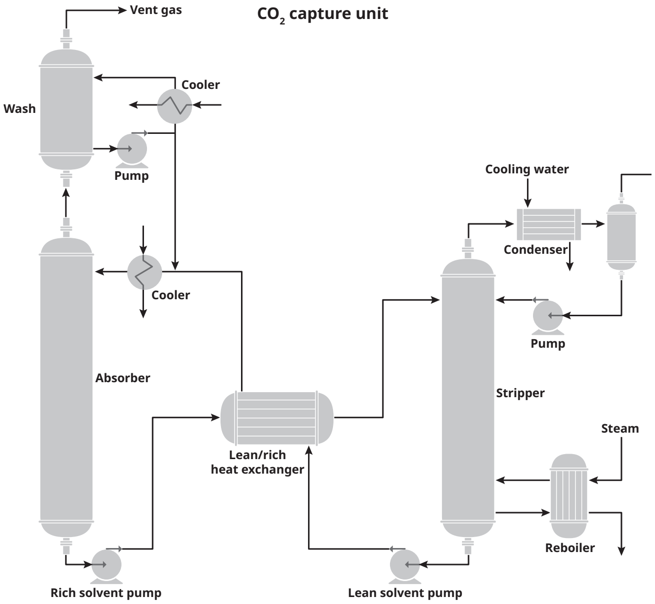

Figure 2: *Effective carbon dioxide removal from mixed gas leaving a combustion or chemical process depends on effective flow, temperature, and pressure measurement and control.*

- Ultimately, the carbon dioxide reaches a site where it can be compressed and driven into the ground, typically into an active oil well to enhance recovery, or alternately, a coal seam, a depleted oil or gas well, or some other existing underground formation.

CCS requires a complex supply chain from one end to the other since few sites have all the necessary elements in one place. Let's examine each link and see how automation can improve efficiency and performance.

Capturing carbon from combustion and more

Carbon capture has two process purposes:

- It removes carbon dioxide from a gas stream because it is a contaminant, as is the case with natural gas reforming to produce hydrogen. In this application, it must capture the maximum amount of carbon dioxide to ensure a pure hydrogen stream.
- It removes carbon dioxide as a pollutant, maximizing the tonnage captured.

Within the second application, a CCS unit may receive flue gas from a combustion process, such as a boiler or fired heater. Many of these units connect to higher volume carbon dioxide sources, such as a rotary kiln for manufacturing lime or cement, or a basic oxygen furnace in a steel mill. Such processes produce higher concentrations of carbon dioxide than conventional combustion, making CCS more efficient, and reducing the capture cost per ton. In a given application, each incremental ton captured from a given unit costs more than the last, so a site must determine when a point of diminishing returns has been reached.

Capture efficiency is dependent on the amount of carbon dioxide in the gas stream in proportion to the solvent circulation rate and overall transfer effectiveness. The more carbon dioxide in the stream, the easier and more efficient it is to capture. Of course, any absorber unit has limits to what it can capture effectively. Where carbon dioxide flow is high, the absorber may be operating at maximum capacity all the time, so the challenge becomes finding ways to increase removal capacity.

On the other hand, with the first application, where the objective is removing the most carbon dioxide possible, the tendency will be to run solvent flow high to maximize capture, but this is costly in terms of emissions and fuel as the solvent must pass through multiple heat exchangers to support stripper effectiveness. Operators must maintain an optimal balance to ensure maximum capture with minimum cost and energy input.

Creating instrumentation and control strategies to achieve this outcome is enormously important due to the costs involved. Absorption is the most expensive step based on operations, energy consumption, and emissions generated. The IEA has calculated that carbon capture can add anywhere from 10% to 40% over the energy consumption of the basic process. This energy penalty has a major effect on the ROI of any given project.

Increasing capture capacity requires thoughtful equipment design and maintenance. Advanced performance engineering software can determine the economic feasibility of a proposed capture unit years ahead of groundbreaking, making cost decisions easier to justify, while ensuring operational success. Algorithms model behavior of complex chemical and thermodynamic systems based on historical data, allowing engineers to predict reliability issues, identify inefficiencies, and estimate energy requirements.

On the other hand, any design flaws or inadequate equipment selection as an installation is being planned will result in inefficiencies, permanent energy losses, and additional fuel requirements over a unit's operational life.

At the same time, all steps taken to improve heat integration, reduce pressure drop, or enhance heat recovery can improve effectiveness and reduce costs. For example, heat exchanger maintenance has an enormous impact on operations. The slightest fouling can quickly increase the amount of energy required per ton of carbon dioxide removed. Basic instrumentation (Figure 3) combined with a data gathering and analysis platform can warn of fouling and indicate clearly how much efficiency is being lost.

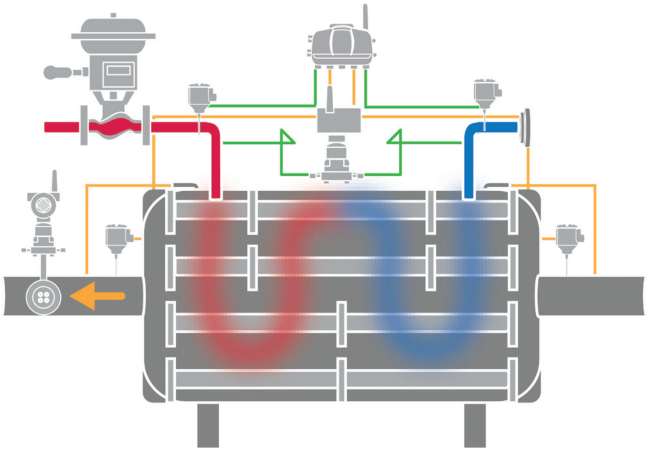

Figure 3: *CCS units depend on multiple heat exchangers, so critical instrumentation is necessary to ensure they're running at peak efficiency.*

Balancing energy

Determining when an optimal energy balance has been reached is challenging. First, flow measurements of both streams, liquid and gas, must be accurate and reliable (Figure 4).

Ultimately, a CCS should isolate as much carbon dioxide as possible while using the smallest amount of energy, and it should avoid exceeding the energy penalty limit for a given application. Even with effective instrumentation, many sites struggle to identify optimum operating conditions across variable flows and gas concentrations. Often it is a trial-and-error process supported by a declining population of experienced operators. Mathematical modeling and simulation techniques, using digital twins and modeling software, can provide better information more quickly and reliably than procedures depending on human skill. A model captures the interactions among different components, in all CCS stages, and recommends settings and operator actions to optimize operations.

Figure 4: *Emerson's Micro Motion Coriolis Flow Meters are often the best choice for solvent flow because they can measure solvent density in addition to flow.*

Compression and liquefaction

After producing a high-purity carbon dioxide stream, multiple stages of compressors and intercoolers condense the hot, captured gas from near-ambient pressure to a much higher pressure suitable for pipeline transmission, typically around 1,100 to 2,200 psi (75 to 150 bar), at 60 to 90 F (15 to 32 C). During this process carbon dioxide is often purposely forced into a supercritical state by increasing pressure and temperature to a level where the molecules exhibit both gas- and liquid-like properties. Under supercritical conditions, carbon dioxide has a much higher density and better solubility, reducing volume and therefore cutting transportation costs.

The characteristics of carbon dioxide under these conditions are common to other large-volume gas transmission techniques. Moving liquified natural gas (LNG) entails similar operational requirements, such as ensuring the reliability of rotating equipment and analyzing the volume and purity of the gas at critical points. Heat exchangers remove the thermal energy generated during compression, while coolers lower the compressed carbon dioxide temperature. Driving this equipment requires large amounts of power, so accurate motor control is required, along with scrupulous maintenance.

One maintenance area is leak prevention, which is critical for carbon dioxide. When concentrated and under high pressure, carbon dioxide is corrosive, and it is a lethal asphyxiant anywhere it accumulates. Containment works both ways as it keeps out contaminants such as sulfur and water, as these form acids. While initial compression usually takes place at the same location as the capture system, prior to entering a pipeline or bunkering on a vessel for transport, additional compression may be necessary before injecting it's carbon dioxide into the ground, increasing the potential for leaks.

Another maintenance area is reliability of compressors and associated machinery. Preventive maintenance technology—using asset management software, edge computing devices, self-diagnostic valves, and remote monitoring solutions—enables a more efficient, predictive approach to conducting inspections and repairs. When considering factors such as operating conditions, load demands, and asset health, preventive software tools schedule maintenance based on the actual condition and performance of the equipment, optimizing maintenance efforts by focusing resources on critical areas that require attention.

Transporting carbon dioxide

Once processed, carbon dioxide must be moved to the site where it will finally be pumped underground. Depending on the distances and volumes involved, carbon dioxide may be in gaseous, liquid, or supercritical states. Handling these forms may require high-strength vessels, tanks, and pipelines, common to handling similar products, such as natural gas in gaseous or liquid form. Any pipelines used must be built to withstand extremely high pressures, with flows supported and regulated by pumps, compressors, and valves. Where distances are relatively short, existing natural gas pipelines are frequently used, operating at lower pressures.

Leakage is a concern, as compressed carbon dioxide, whether in its liquid or supercritical phase, tends to leak through joints and other fittings. All equipment along the transport route must be carefully designed and maintained with appropriate seals, gaskets, and welds. Valves and other final control elements (Figure 5) are potential leak points, especially in high-pressure situations, as are sensor probes penetrating pipe walls.

Figure 5: *Control valves for carbon dioxide service must be carefully specified.*

Temperature and pressure fluctuate during transport due to changes in ambient conditions or shipping operations. If not controlled, these can result in carbon dioxide solidifying, leading to blockages, restricting flow, and eventually causing equipment failure and loss of containment. Corrosion is always a concern because it can cause ruptures, and it can also allow contaminants to enter the flow stream, including water and hydrogen sulfide. These form acids, leading to more corrosion and problems downstream. Small leaks are inevitable, so detecting and fixing them before they develop into bigger problems is critical.

Depending on the delivery route's complexity, there could be several handoff points at which carbon dioxide changes ownership. These custody transfer points usually include checking the gas for purity, verifying pressure, and most of all, volume. Producers and transporters must report the exact amounts at all steps, from the initial generation to final injection at the well site. Moving from point to point, it is possible to determine any volume lost through leaks and other unintended releases. Custody transfer metering falls under complex regulatory requirements, especially volumes necessary to report for carbon taxes and emissions trading systems.

Injection in the ground

The ultimate destination for captured carbon dioxide is into the ground where it will stay (Figure 6). As mentioned earlier, most carbon dioxide is injected into active oil and natural gas wells to enhance recovery. If the well is managed correctly, the carbon dioxide stays in the ground even though the other products are being recovered, plus, the value of any additional oil and gas produced offsets the carbon capture cost. In other situations, carbon dioxide is being injected into inactive wells where it is absorbed by geological formations.

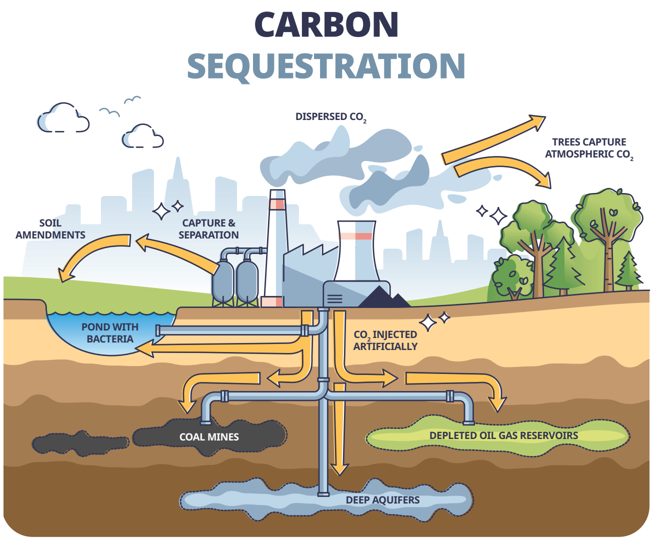

Figure 6: *Many geological formations are well suited to carbon dioxide storage.*

The goal is to inject as much carbon dioxide as possible down the well up to the point where the geology remains sound, and then keep it there under pressure indefinitely. Many of the same kinds of efficiency, reliability, and safety challenges that apply to oil and natural gas drilling and production operations apply here as well. Injection pressures can be very high, often up to 15,000 psi (1,035 bar), requiring careful monitoring of the compressors and injection equipment.

Three main types of geologic formations are suitable for long-term geologic storage: aquifers, abandoned wells, and unmineable coal seams. Vast underground formations several kilometers below the surface, called deep saline aquifers, have the capacity to store significant volumes of liquified carbon dioxide without encroaching on freshwater supplies. Abandoned oil and natural gas well sites have well-established geologic properties and infrastructure, making them particularly attractive for CCS use. Deep unmineable coal seams tend to absorb carbon dioxide, effectively trapping the pressurized fluid underground. A suitable number of coal formations are known to exist in North America, Europe, Asia, and Australia.

A practical path to climate change mitigation

The concept of reducing carbon dioxide emissions through use of CCS has come a long way. Where it was once perceived as an extravagance with little practical value, it is now a valid and economical tool for mitigating climate change. The pressing need to curb greenhouse gas emissions and combat global warming has reshaped the narrative around CCS, making it a pathway to achieving deep decarbonization, even as many industrial and transportation sectors still depend on fossil fuels.

This changing perception is providing impetus for public- and private-sector efforts on research, development, and deployment of CCS. Governments, industries, and organizations across the globe are actively pursuing ambitious projects and passing landmark legislation to acknowledge its potential to meet ambitious climate targets and accelerate the shift towards sustainability.

There is still much work to be done to push further technological advancements, cost optimization, public acceptance, and regulatory frameworks that support implementation. Addressing these challenges necessitates continuous innovation, collaboration, and more robust policy support to realize large-scale deployment of CCS.

Given the urgency behind decarbonization, embracing CCS as a critical component of a comprehensive toolkit to combat climate change has become an imperative. Fortunately, with the advances made possible by innovative automation technologies, along with continued public and private collaboration, CCS is set to play a pivotal role in protecting the environment for generations to come.

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